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Grazing activities in the Southern Central Pyrenees during the last millennium as deduced from the non-pollen palynomorphs (NPP) record of Lake Montcortès

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Abstract

Human activities during the last millennium have shaped most of the present-day landscapes. During this time, in the southern central Pyrenees several climate periods and phases of variable human disturbance have driven varied landscape responses. In previous studies of the sediment deposits in Lake Montcortès (southern central Pyrenees) several climatic shifts (including the Medieval Climate Anomaly and the Little Ice Age), as well as forest clearance by fire, agriculture and cattle raising as the main human impacts were recorded since Medieval times. In this work we use non-pollen palynomorphs (NPP) on the same sequence to reconstruct the different human activities, with a special focus on grazing, at an average resolution of around 30 years per sample. Independent NPP proxies for fire and forest

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clearance were found, supporting former studies. Moreover, the NPP record shows four periods of high abundance of coprophilous fungi: 1) 830 - 865 CE); 2) 1120 - 1290 CE, 3) 1530 - 1795 CE; and 4) 1865 - 1880 CE. These four periods correspond to phases of increased livestock farming, as reported in historical documents. Comparison of pollen, historical documents, and NPP records show that the impact on landscape dynamics during the last millennium have been mostly related to variable human population density controlled by historical, political and cultural changes in the Pyrenean mountains. Moreover, the use and comparison of several independent proxies have highlighted the strength of the indicator value obtained.

Keywords: fires; forest clearance; human disturbance; livestock; non-pollen palynomorphs; Pyrenees.

1. Introduction

During the last decades, the study of past vegetation history has been highlighted as essential for the understanding of current and future biodiversity and ecosystem dynamics (Willis et al. 2007; Rull 2012 IPCC 2013). These studies have provided information about past community trends, allowing identification of the main drivers involved in vegetation changes as a response to internal and external pressures (e.g., Vegas-Vilarrúbia et al. 2011, Pérez-Sanz et al. 2013). Among these forcings, climate change and human activities have been the main factors responsible for the shaping of current landscapes during the last millennia. However, the coupled action of these drivers and their interactions often make it difficult to untangle the climatic from anthropic signals in paleorecords. This handicap is especially problematic in studies based on one or few related proxies due to eventual circular reasoning (Rull et al. 2011). The analysis of microfossil remains of biological origin other than pollen and pteridophyte spores present in palynological slides, known as non-pollen palynomorphs (NPP),

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has proved to be a useful tool to disentangle the nature of the forcings involved (Loughlin et al. 2018). NPP provide additional information due to their independent nature in relation to other proxies (van Geel 2001; Montoya et al. 2012). In this sense, NPP studies have been able to efficiently record the human footprints on landscapes, mostly at local scales (deforestation, fire practices or grazing), which can remain unnoticed using the usual proxies (van Geel et al. 1983, 2003).

NPP studies developed so far in the European mountains have demonstrated the intense human management of these landscapes (Argant et al. 2006; Menozzi et al. 2010). In the Pyrenees (SW Europe), where the present study is located, efforts have been focused on the reconstruction of the human impact on vegetation changes during the last millennia. These studies have revealed a wider range of activities than previously thought, including grazing, deforestation, agriculture, hemp retting or mining (Riera et al. 2006; Cugny et al. 2010; Ejarque et al. 2009, 2010; Miras et al. 2007, 2010; Rull and Vegas-Vilarrúbia 2014; Rull et al. 2011). According to these studies, human activities are noticeable in the highlands since the start of Neolithic (ca. 6000 BCE). The maximum level of human impact occurred during the last millennium (González-Sampériz et al. 2017). Moreover, the comparison among records has revealed asynchronies in human impact between different study areas, and in some cases, even within the same study area. In these cases, the local-scale information provided by the NPP (Ejarque et al. 2010; Miras et al. 2010) highlighted the key role of social changes (cultural, political, and/or demographical) in shaping the present-day landscapes.

The present paper is focused on the NPP analysis of the Lake Moncortès record (southern central Pyrenees) during the last millennium. Previous studies of the lake sediment have provided detailed understanding of the lake sedimentological, geochemical, paleolimnological and paleoecological evolution during the last centuries (Corella et al. 2011, 2012, 2014, 2015, 2016, 2017; Rull and Vegas-Vilarrúbia, 2014, 2015; Rull et al. 2011; Scussolini et al. 2011,

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Vegas-Vilarrúbia et al. 2018, Trapote et al. 2018). These studies revealed a complex interplay between climate and human activities, sometimes in a synergistic fashion, in shaping modern landscapes. A decisive advantage of the Montcortès sequence is the high chronological resolution provided by their varved (annually laminated) sediments, which have led to a robust age model (Corella et al. 2012, 2014, 2016). A comprehensive review of historical documents (Rull et al. 2011; Rull and Vegas-Vilarrúbia, 2015 and literature therein) has also provided a detailed account of political, social and economic changes in the region. The aim of this paper is to obtain independent and complementary evidence for regional landscape management, with emphasis on grazing, pasture and fire history at a local scale based on the analysis of NPP. Also, the comparison of NPP data with other proxies contributes to clarify the interplay among the different drivers involved and, hence, to elucidate the human role in shaping the landscape.

2. Study Area

2.1. Geographic location

Lake Montcortès, thereafter LM (42°19'N - 0°59'E, 1027 m elevation), is a karstic lake located in the Pallars region (Catalonia), in the southern flank of the central Pyrenees, NE Spain (Figure 1). The lake is situated in a small catchment characterized by Triassic limestones, marls and evaporites, and Oligocene carbonatic conglomerates (Rosell 1994; Gutiérrez et al. 2012). LM has roughly a circular shape of 400-500 m diameter and a maximum water depth around 30 m near the center, which is fed mainly by groundwater, with intermittent smalls creeks and scattered springs (Camps et al. 1976; Modamio et al. 1988). The lake is located within the sub-Mediterranean bioclimatic domain, in a transitional climatic area with a strong rainfall gradient (Rull et al. 2011, 2017; Corella et al. 2012). Mean temperatures range from 1.9°C in January to 20.3°C in July (Annual average: 10.6°C). Total annual precipitation is 860 mm, being March

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(46.6 mm) and May (99.2 mm) the driest and wettest months respectively (Corella et al. 2011). The lake lies near the altitudinal boundary between the Mediterranean lowlands and the Middle Montane belt (Vigo 2008) and it is surrounded by three major forest communities: (i) Evergreen oak forests; (ii) Deciduous oak forests; and (iii) Conifer forests (Folch 1981). An exhaustive floristic inventory of LM surroundings has been performed by Mercadé et al. (2013). Regarding human occupation, the area is nowadays underpopulated compared to former periods and the main economic activities are tourism and related services. Agricultural land uses are minor, limited to cereal cultivation and livestock pastures (Rull et al. 2011).

2.2. Previous works on LM

Although detailed explanations of the different proxies used to date have been published elsewhere (Table 1), a brief summary of the main environmental events inferred is provided here in order to frame the interpretation of the results obtained in this study (Figure 2). During the last two millennia, several intervals of low clastic inputs have been recorded and related to the Iberian-Roman Humid Period (500 BCE – 400 CE), the Little Ice Age (LIA; c. 14^{th} – 19^{th} centuries) and the last century, whereas periods of high clastic inputs have been related to the Medieval Climate Anomaly (MCA, 9^{th} – 13^{th} centuries), and the end of the LIA (late 19^{th} century). Both intervals of high sediment delivery to the lake coincided with periods of intense farming and high human pressure in the watershed. The anthropogenic impact on the landscape during these periods was also revealed by the pollen record (Rull et al. 2011), and during the last 500 years, some of the anoxic processes registered at the lake were also linked to human activities (Vegas-Vilarrúbia et al. 2018). Based on a detailed pollen analysis with species identification thanks to an exhaustive botanical survey (Mercadé et al. 2013), two main phases of agricultural development were registered, centered at 9 th-14^{th} (A1) and 16 th-19^{th} centuries (A2) (Fig. 2). These two periods differed both in the cultivated species of interest and in the land use system (such as fire clearance or rotation) (Rull and Vegas-Vilarrúbia 2015).

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Regarding climate, the scarcity or absence of diatoms between 800 and 1250 CE has been considered indicative of low lake levels during these periods (Scussolini et al. 2011). Since 1250 CE onwards, diatom assemblages indicate a lake level recovery, with the occurrence of a short-lived drier and cooler phase dated to 1335-1390 CE (Scussolini et al. 2011). In this sense, the detailed analysis of the sediments evidenced two main periods of extreme multiple rainfall events centered at 927 to 1398 CE and 1844-1894 CE that coincided with historical floods from the nearby Segre River (Corella et al. 2014, 2016). The pollen analysis of sediments corresponding to the last millennium also record two major climatic shifts based on the vegetation dynamics: (i) a warmer and likely drier climate (or higher rainfall seasonality) during MCA (1185-1375 CE); and (ii) a colder and moister LIA (1375-1580 CE) (Rull et al. 2011). Minor climatic changes were possibly masked by the consequences of human impact. A high resolution study of microfacies performed by Corella et al. (2012) identified several intervals such as 1446-1598 CE, 1663-1711 CE and 1759-1819 CE as colder periods, whereas 555-738 CE, 825-875 CE, 1010-1322 CE and 1874 CE -present day where characterized by warmer conditions. Moreover, this study suggested the decoupled action of human practices and climate upon landscape during the last two centuries, when anthropogenic activities decreased despite a warmer and more favorable climate (Corella et al. 2012).

3. Methodology

The coring and sampling methodologies have been explained in detail in Corella et al. (2011) and Rull et al. (2011); here, a summary will be provided. The NPP reported in this paper were analyzed in the same palynological slides of Rull et al. (2011). For palynological analysis, samples were taken from the core MON04-1A-1K (obtained with a Kullenberg coring platform), every 10 cm from the upper 3.6 m, roughly corresponding to the last millennium (Table 1). Pollen and geochemical data from Rull et al. (2011) and Corella et al. (2011) respectively were

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obtained in the same composite sequence and they will be used to compare with the NPP record (Table 1).

Palynological samples consisted of ~3-5 g of sediment that were processed using standard methods, including NaOH, HCl and HF digestions and density gradient centrifugation (Bennet and Willis 2001). Two Lycopodium tablets (Lund University: batch n° 483216: 18,583 spores/tablet) were added to each sample prior to chemical treatment, and the final slides were mounted in glycerine jelly. NPP abundance was expressed as percentage with respect to the pollen sum, including all pollen taxa except aquatic and semi-aquatic plants (Rull et al. 2011): Cyperaceae, *Cladium, Myriophyllum, Pinguicula, Potamogeton, Ranunculus, Typha/Sparganium*-type and *Utricularia*. NPP identifications were based on Bell (2005), Cugny et al. (2010), Ellis (1971, 1976), Gelorini et al. (2011), Hooghiemstra and van Geel (1998) and references therein, López-Vila et al. (2014), Montoya et al. (2010) and Revelles and van Geel (2016). Whenever possible, unidentified NPP have been assigned to previously described morphotypes using the codes of several already existing classifications (University of Amsterdam, University of Ghent, Botanic Institute of Barcelona, and University of Toulouse-le Mirail) (Table 2). New morphotypes have been described for the first time and named using a code from our institution (IBB-) and a sequential number (Appendix A). Diagrams were plotted with Psimpoll 4.27 (http://chrono.qub.ac.uk/psimpoll/psimpoll.html) and zonations were performed by "Optimal Splitting by Information Content" (OSIC), using the broken stick method to determine the significant zones (Bennett 1996). The age model used in this work is based on 210^{Pb} dating and varve counting recently published (Corella et al. 2014, 2016) that revisited the former age-depth model based on radiocarbon dating (Corella et al. 2011). The most recent chronology of the lake sediments only differs 7% with respect to previous ones (Corella et al. 2014). In this work, new dates have been assigned to the former palynological samples published in Rull et al. (2011) (See Corella et al., 2014, 2016 for further details about the age-depth model). In this sense, comparison with other proxies from previous studies have

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been made using the new chronology unless it is specified otherwise. A final summary figure of selected proxies was plotted by age in R version 3.82 using the package "rioja" (Juggins 2017), which included log10 data transformation of the charcoal influx values.

4. Results

A total of 58 morphotypes were found considering fungal spores (36), algal remains (8), zoological remains (6), pteridophyte spores (4), pollen from aquatic/semi-aquatic plants (3) and bryophyte spores (1). NPP often present low abundances or even single appearances in the paleoecological records, which decreases the strength of the potential indicator value of the remain found; here, to make them visible in the diagram, only NPP that appear in more than one sample with percentages respect to the total abundances per sample higher than 7% have been plotted in the diagrams (Figures 3 and 4). As the NPP percentages have been calculated based on the pollen sum, the significant zones shown in the diagrams (Figures 3 and 4) are those previously defined for the pollen analysis in Rull et al. (2011) that represents the vegetation dynamics of LM including the updated chronology.

4.1. Zone MON-1 (360-325 cm, 828-915 CE, 4 samples)

The base of the zone is characterized by high values of *Chaetomium, Glomus, Sordaria*-type, *Neurospora crassa, Delitschia* Types I and II, *Sporormiella*, UG-1118 and the new morphotypes IBB-47 and IBB-40 (Figure 3). At the middle part of the zone there is a peak of *Coniochaeta cf. ligniaria* (hereafter *Coniochaeta*), followed by a decreasing trend until the top of the zone (Fig. 3). Regarding aquatic or semiaquatic organisms (Figure 4), Cyperaceae and *Concentricystis* (also known as *Pseudoschizaea*) show the highest values. Monolete fern spores show an increase, although other spores are present as well. Acari and Chironomidae remains show higher values compared to the following zones. Bryophyte spores peak at the middle of the zone.

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4.2. Zone MON-2 (325-203 cm, 915-1185 CE, 12 samples)

Most of the morphotypes already mentioned follow the same trends initiated in Zone MON-1, such as IBB-47, *Chaeotomium, Coniochaeta, Sordaria*-type, *Sporormiella* and UG-1118, though in slightly lower abundances (Fig. 3). *Glomus* disappears at the beginning and reappears at the middle of the zone, just after the peaks of *Entorrhiza, Gelasinospora* and *Kretzschmaria deusta* (formerly known as *Ustulina deusta*; hereafter *Kretzschmaria*). At the end of the zone there is a general increasing trend in the taxa that were dominant at the base of the zone, as well as in IBB-3, IBB-29, IBB-46, IBB-47, and IBB-44 (Fig. 3). At the beginning Cyperaceae show lower percentages than in the previous zone, followed by an increasing trend since around 300 cm (ca. 950 CE) (Fig. 4). Bryophyte and pteridophyte spore abundances decrease, whereas algal remains show the opposite trend, with an abrupt peak of *Tetraedron* (and to a minor extent, of *Spirogyra*), at the base of the zone and another of *Botryococcus* at the mid/upper part of the zone. At the top of the zone, *Pediastrum* values increase. *Concentricystis* and Acari are characterized by lower percentages than in the former zone (Fig. 4).

4.3. Zone MON-3 (203-112 cm, 1185-1373 CE, 9 samples)

The beginning of Zone MON-3 is marked by high percentages of several morphotypes including *Chaetomium, Coniochaeta, Glomus, Sordaria*-type, *Sporormiella* and UG-1118 and, to a minor extent, IBB-3, IBB-29, IBB-31*, Podospora, Kretzschmaria*, IBB-46, Sordariales, IBB-18 and IBB-44. These abundances reflect in many cases an increasing trend that started at the top of the previous zone (Fig. 3). IBB-47 also peaks at the beginning and completely disappears afterwards. Indeed, after the high values that characterize the bottom part of the zone, there is a general decreasing trend and the disappearance of some of the taxa around the middle of the zone. Despite the decreasing trend, *Chaetomium* and *Sordaria*-type show the highest abundances at the top of the zone (Fig. 3). Concerning taxa related to aquatic environments (Fig. 4), bryophyte spores (and Monolete fern spores) and *Typha/Sparganium* also show an

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increase at the beginning of the zone, followed by, in the case of the spores, a decreasing trend, and the disappearance until the upper part regarding *Typha/Sparganium*. On the contrary, *Cladium*-type appears in the middle of the zone and retains its abundance until the top. Algal remains display different trends: *Tetraedron* has a single peak at the middle zone, *Concentricystis* shows higher abundances than in the previous zone, whereas *Spirogyra, Botryococcus* and *Pediastrum* mimic the decreasing trend of bryophyte spores and *Typha/Sparganium*. Acari remains are present with low and discontinuous values during the lower half of the zone and then disappears upwards for the rest of the sedimentary record.

4.4. Zone MON-4 (112-72 cm, 1373-1590 CE, 4 samples)

This zone is marked by the general disappearance of almost all fungal taxa except for UG-1118, which appears again during this zone, though in lower abundances than in previous zones. *Delitschia* Type I shows two minor peaks. At the middle of the zone, around 95 cm (ca. 1450 CE) firstly *Chaetomium*, and then *Sordaria*-type and *Sporormiella* are characterized by an increasing trend (Fig. 3). *Cladium*-type slightly increases at the beginning but declines from the middle part of the zone upwards (Fig. 4). Bryophyte spores are absent. Concerning algal remains, *Spirogyra* and *Botryococcus* show slightly higher abundances, and *Concentricystis* percentages decrease compared to the previous zone. Chironomidae remains peak at the middle zone, and Cladocera remains and *Centropyxis*-type appear for the first time in the record, though with very low values, at the end of this zone.

4.5. Zone MON-5 (72-20 cm, 1590-1865 CE, 5 samples)

A general increase in fungal spores' abundances is observed throughout this zone, especially marked for *Chaetomium, Sporormiella* and UG-1118 (Fig. 3). *Sordaria*-type shows a percentage increment at the bottom, but it decreases in the upper half of the zone. Other taxa such as *Glomus*, IBB-29, IBB-6, IBB-46, IBB-40 and *Arthrinium muelleri*-type (Ellis, 1971) peak in the middle part of the zone. Cyperaceae percentages are higher than in MON-4 and remain

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constant during the bottom part of this zone, slightly decreasing at the top. *Typha/Sparganium* shows an abrupt peak at the beginning of the zone, and a decreasing trend afterwards. Minor peaks at the beginning are observed in *Cosmarium* and *Plumatella* abundances (Fig. 4). *Cladium*-type disappears prior to the peak of *Typha/Sparganium*, without further recovery. *Concentricystis* and *Spirogyra* present slightly higher values than in MON-4, and *Botryococcus* shows a decreasing trend. *Pediastrum* reappears in this zone but with low values.

4.6. Zone MON-6 (20-5 cm, 1865-1881 CE, 2 samples)

The top zone is marked by the high values of fungal spores, especially from *Sporormiella*, but also *Chaetomium* and *Sordaria*-type (Fig. 3). Minor contributions come from *Coniochaeta, Glomus*, IBB-3, IBB-29, *Delitschia* (Types I and II), UG-1118, *Bispora*-type, and IBB-45, among others. Bryophyte spores, Cyperaceae, Monolete fern spores, *Concentricystis* and Chironomidae also increase. On the contrary, *Typha/Sparganium, Spirogyra* and *Botryococcus* show lower values than in MON-5 (Fig. 4).

5. Interpretation and Discussion

5.1. Land use changes from palynological records and documentary sources

The oldest section of the record (9th century) was characterized by the occurrence of forest fires as inferred from the charcoal curve (particles >5 μm). Fungal spores related to local fire events (*Neurospora crassa*) and the presence of decayed and/or charred wood fed spores (*Coniochaeta* and *Gelasinospora*) (van Geel and Aptroot 2006) are in agreement with the occurrence of fires in the catchment prior to the 10th century (Fig. 3). These fungal spores are assumed to come from a nearby area due to their low dispersion capacity, whereas charcoal particles could be transported from fires up to almost 20 km far from the coring site (Whitlock and Larsen 2001). The practice of fire with agricultural purposes was common in the Pallars

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region especially aimed to provide pastures and hence avoid the long-distance winter transhumance (Marugan and Oliver 2005). This practice was abolished in the region in 948 CE, and it can be clearly observed as a decrease in the charcoal record and by the disappearance of the fungus *Neurospora* that it is linked to local fire (Fig. 5). However, the increase in forest fires during the 12th-13th centuries previously observed in the charcoal record (Rull et al. 2011; Rull and Vegas-Vilarrúbia 2015) does not correspond with any increase of these fungal spores, which could be interpreted as an increase in the fire incidence at a regional scale not affecting the lake catchment (Figures 3 and 5). Synchronous to the charcoal curve, the abundance of *Glomus* at the beginning of the record suggests erosional processes due to the human land management (Anderson et al. 1984), in agreement with high values of Ti (Fig. 5). Besides erosion, its ensuing decrease could be explained by the coeval decrease of *Pinus* owing to fire, with which *Glomus* likely maintained symbiotic relationships (Rull et al. 2011; Zhou et al. 1997). Therefore, *Glomus* abundances could be related not only to erosion, but also to changes in coniferous forest cover. Remains from aquatic and semi-aquatic organisms like bryophyte spores, *Concentricystis*, and Acari suggest low lake levels until the second half of 10th century (Fig. 4), in agreement with previous sedimentological and geochemical – based reconstructions (Corella et al. 2012).

The periods between the 10th - 14th and 16th – 19th centuries have been defined as intervals of agricultural development around LM, where a wide range of cultivars were used (Fig. 5). Within the first agricultural interval, the 11th and 13th centuries witnessed a significant increase in human population around LM, and also a shift to more controlled and permanent land use (Marugan and Oliver 2005). In a detailed analysis of the pollen of weeds and crops present in the sediments of LM during the last millennium, Rull and Vegas-Vilarrúbia (2015) suggested the establishment of a rotation system of the land in mosaics alternating between crops and pastures. Among NPP the increase in *Glomus* abundance points to increased erosional processes derived from a more intense soil disturbance, again matching with an increase in Ti

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reflecting higher erosion and runoff rates in the watershed (Fig. 5; Corella et al. 2011). More abundant algal remains (Fig. 4) favor the hypothesis of higher lake level phases during 11th and 12th centuries as previously interpreted (Corella et al. 2011; Rull et al. 2011; Scussolini et al. 2011).

A significant crisis leading to a population decline occurred during 14th and 15th centuries, coinciding with wars and the Black Death at the cooling onset of the LIA. The NPP record shows the almost total disappearance of fungal spores related to human activities (Zone MON-4, Figs. 2 and 5). Slightly higher lake levels were inferred on the basis of a *Botryococcus* increase (Fig. 3; Rull et al. 2011). A return of human activities around LM occurred during the second half of 16th century (Bringué 2005), manifested in the paleoecological record by: i) an increase in fire incidence, ii) the eutrophication of the lake inferred from the dramatic *Typha/Sparganium* peak (Rull et al. 2011; Scussolini et al. 2011), iii) the increment of sediment delivery to the lake (Corella et al. 2011, 2012) and, in the NPP record, iv) by the increasing trend of *Chaetomium* and the return of *Glomus* coeval to the second phase of agricultural development (Fig. 5).

The isolation of the Pallars region during the 18th -19th centuries due to the absence of a well-developed road system led to a subsistence economy, with some diversification in order to increase self-sufficiency. During this period, the southern lowlands and the mountains to the north were substantially different from a socio-economic point of view (Farràs 2005), and LM is located in an intermediate area between both. Based on the NPP record, from c. 1865 to 1880 CE *Glomus* abundance reflected some erosional processes by likely land management, in agreement with the Ti curve (Corella et al. 2011, Fig. 5). Although the charcoal record did not show any significant change (Fig. 4), fire-related spores such as *Coniochaeta* and *Neurospora* slightly increased (Fig. 3 and 5). However, during this interval the pollen record pointed to a forest recovery, mainly manifested by an increase in *Pinus* percentages (Fig. 5). Pine species are widely known for having huge pollen production with long distance dispersal capacity

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(Cañellas-Boltà et al. 2009). On the other hand, the different behavior between charcoal and Ti curves (proxy for runoff produced just in the catchment) along the record also points to a mixed source area of charcoal, obtaining particles from close or far locations, or from both at the same time (Fig. 5). Taking these evidence into account altogether, this interval could be interpreted as the occurrence of patchy local fires in a regional context of reforestation, but the NPP results do not point to agricultural fire practices as the main economic activity in the area as we will explain below.

The paleoecological studies in nearby Pyrenean locations on human activities' trends generally agree with LM´s reconstruction, although they also highlight great heterogeneity in land use through time and space. The near Lake Estanya (Fig. 1) showed high levels of erosion based on *Glomus* abundances from 820 until 1075 CE, with clear indicators of grazing and fires (Riera et al. 2006). The 11^{th}–13^{th} centuries were characterized in the catchment area of Lake Estanya by low abundances of anthropogenic disturbances' indicators (for erosion, grazing, fires), opposite to LM and interpreted as a change from extensive grazing to arable activities. This asynchrony could be due to: (i) the different altitude of both sites, with higher human pressure in LM during MCA due to more favorable climatic conditions in the high lands (Corella et al. 2011; Rull et al. 2011); (ii) some taphonomic influence, due to the location of the records within the lake basins (littoral en Estanya; distal in Montcortès) (Raper and Bush 2009; Parker and Williams 2011); or (iii) chronological uncertainties based of different age models: radiocarbon (centennial to decadal resolution) *vs*. varve counting (annual resolution). On the contrary, LIA was characterized in both lakes by very low abundances of fungal spores; this decrease was not recorded in the Pradell fen (Ejarque et al. 2009). This high altitude location (1975 m asl; Fig. 1) reflected multiple human practices (e.g., mining, smelting, grazing, cropping, charcoal and tupertine production and tree felling), with a maximum human impact during the 1600-1900 CE interval, and woodland recovery and farming retreat during the 1330-1550 CE economic and demographic crises (Ejarque et al. 2009). Such heterogeneity in land

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use was also observed spatially in the Madriu Valley, eastern Pyrenees (Ejarque et al. 2010). In this work, Ejarque et al. (2010) studied past human management at a micro-regional scale (three records within ca. 1700 ha), and concluded that landscape variability is not always necessarily linked to topographic or climatic parameters, highlighting the role of social, economic and cultural trends in the land-use organization and landscape shaping since Prehistory.

Outside the Pyrenees, the Lake Arreo record (Fig. 1) shows some parallel trends with Lakes Estanya and Montcortès, e.g., a high fire frequency interval around 800 CE interpreted as caused by Arab incursions in the area (Corella et al. 2013). A high anthropogenic pressure was also suggested by the occurrence of human impact indicators and higher clastic inputs to the lake until 10th century, synchronous to the first medieval settlements. In Arreo, fires and erosion events seem to be closely related, given the parallel curves of charcoal particles and *Glomus*. As in LM, the most intense land use period in Lake Arreo occurred between 890 and 1180 CE, with deforestation and farming activities likely triggering an increase in the clastic run-off, followed by a period of land abandonment, and a further recolonization from 1600 CE onwards (Corella et al. 2013).

5.2. Cattle raising around Montcortès: the coprophilous fungi record

The curves of total coprophilous fungi show the trends of *Sordaria*-type, *Podospora*-type and *Sporormiella* altogether, expressed in percentage and concentration values (Fig. 3). Although there is a debate regarding the morphotypes that should be included as proxies for grazing (Baker et al. 2013), we have only used already known obligate coprophilous fungi and well defined spore types (Cugny et al. 2010, Ejarque et al. 2011). These curves show an almost continuous presence of coprophilous taxa along the record (except for the zone MON-4, coeval to LIA), suggesting grazing pressure to some extent. The NPP record is in agreement with the documentary archives, which have highlighted the historically importance of livestock in the

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Pallars region, with vertical transhumance being practiced since antiquity (Bringuè 2005), and the abandonment of the practices very recently after the 19th century land confiscation. Moreover, given the geographical location of LM, use of the livestock had an essential communication and transport function. Based on the coprophilous fungi abundance, four periods of pasture activities around LM can be suggested (Fig. 4):

(i) 830-865 CE: The smaller intensity of this peak could be related to the increase in population caused by the northward Muslim expansion (Marugan and Oliver 2005) and the recovery of isolated livestock practices during the Visigoth epoch until the arrival of the Carolingians. Since the 9th century long-distance transhumance was practiced although not extensively, leaded by the religious monasteries that were also the owners of the available summer pasturelands (Marugan and Oliver 2005). During the 9th and 10th centuries, the equine livestock was crucial for the communication trades, and also had a political value given the military function (Marugan and Oliver 2005). Documentary sources indicate an increase of the mineral trade in the region mainly for horseshoes. The isolated peak in the coprophilous concentration curve at around 940 CE (306 cm depth) corresponds to a sample from a thick turbidite and consequently it is not coherent with any taxa percentages (Fig. 2);

(ii) 1120-1290 CE: This interval of high dung indicators' values is coeval with the highest population density documented in the area (11th-13th centuries), when the expansion of cattle farming and the beginning of large vertical and horizontal sheep transhumance occurred (Marugan and Oliver 2005). Documentary evidences also show the onset of manure demands as fertilizer since the 12th century parallel to agriculture expansion (Fig. 2) (Marugan and Oliver 2005);

(iii) 1530-1795 CE: Previous studies based on the pollen record did not show conclusive evidence about increase in pastureland during the 16 th-18th centuries

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despite the occurrence of an agricultural development phase (Fig. 5; Rull and Vegas-Vilarrúbia 2015). However, the regional increase in pastures reported in the historical records during this period is coherent with the high percentages of coprophilous taxa in the Montcortés record. Also a new route with the nearby Montsec area was established in 1687 CE (Fig. 2), which promoted an increment in the number of muleteers in the region. At the end of the 18th century, the use of manure as fertilizer reached a peak due to the high cattle and sheep populations in these montane locations.

(iv) 1865-1880 CE: This interval shows the highest levels of coprophilous fungi (Fig. 3) and it coincides with the subsistence economy carried out during the pre-capitalism period in the area, when animal husbandry markets were crucial for the inhabitants (Farràs 2005). It has been reported that more than 88,000 sheep were in transhumance in 1860 CE in the area (Farràs 2005). The palynological data indicate that LM watershed was managed as a mountain area, with forestry and grazing as main activities (Fig. 5), although some *Secale* and *Cannabis* cultivation also occurred (Fig. 5; Rull and Vegas-Vilarrúbia 2015). The increase in grazing activities around LM during this period coincided with higher extreme rainfall events in the area (Fig. 2; Corella et al., 2014) that resulted in higher erosion rates in the lake watershed (Fig. 5). This pattern has also been documented in other Mediterranean catchments where the coupled effect of deforestation and grazing with higher frequency of extreme run-off events resulted in higher sediment yield during the late 19th century (Rodriguez-Lloveras et al. 2017).

Periods of high pasturage in nearby sequences inferred from coprophilous fungi have been dated at 160-820 CE and 1770-1990 CE in Lake Estanya (Riera et al. 2006); 1550-1650 CE and 1800-1900 CE in Pradell fen (although there is a peak of *Sordaria*-type, not considered coprophilous by the original authors, between 900 and 1080 CE) (Ejarque et al. 2009); 890-

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1190 CE and 1850-1900 CE in Lake Arreo (Corella et al. 2013); and 1300-1500 CE and 1900-1990 CE in Sourzay peat bog (Mazier et al. 2009). Considering all these records, the maximum abundances of grazing occurred in the Pyrenees at 1770-1990 CE (Lake Estanya), 1530-1795 CE (LM), 1550-1650 CE (Pradell fen), and 1300-1500 CE (Sourzay peat bog). In spite of chronological uncertainties based on the different age models applied in the studied sequences, it is noticeable that these records span almost the last millennium without much overlapping (Fig. 5). The temporal asynchrony could be mainly related to: (i) regional differences of land use history related to local demographic and political causes, and (ii) the variable landscape impact of the wide range of human activities associated with husbandry: meat consumption, farming, clothing, or transport among others.

Some studies have reconstructed grazing history based just on the pollen record. However, given the different source and dispersion of the pollen taxa, interpretations can be speculative or inaccurate (for an accurate methodology, see Mazier et al. 2009). This could be especially severe in landscapes with great land use heterogeneity (Graf and Chmura 2006). Based on the palynological record of LM, Rull et al. (2011) and Rull and Vegas-Vilarrúbia (2015) inferred past grazing from meadows/pastures and weed pollen taxa indicators. The pollen and coprophilous curves from LM mimic the general trends *sensu lato*, suggesting that the selected pollen taxa in LM provide mostly local information despite some regional influence (e.g. *Pinus*). However, it should be noticed that fungal spores define better the intervals with higher grazing, matching more accurately with the available historical documents. Another handicaps for pollen as the only proxy for grazing activities are due to: (i) The lack of agreement of the taxa that should be included; and (ii) The generalist nature of some of the pollen taxa used (not specific or exclusive of pastures), which may cause some overlapping with other weeds or ruderal taxa not used by the livestock. This lack of homogeneity in the indicator value also prevents further comparison between different records across regions. Therefore, the use of

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NPP in addition to pollen studies is encouraged to obtain an accurate and independent proxy for grazing reconstructions.

6. Conclusions

A differentiation between local and regional fires and other human activities has been possible through the use of specific fungal spores' morphotypes. The high resolution provided by the varve chronology has allowed comparison between NPP trends and historical documents. The coprophilous fungi record has shown four main periods of high grazing pressure in LM watershed (830-865 CE, 1120-1290 CE, 1530-1795 CE and 1865-1880 CE), similar to other reconstructions based on pollen and geochemical/sedimentological proxies, but narrowing down the intervals and providing a more coherent evolution with the available historical documents. The large local scale variability of past human activities in the Pyrenees during the last millennium demonstrated by the limited NPP records available highlights the strength of this analysis in reconstructing local anthropogenic impact, and therefore, its use is encouraged in routine pollen based studies. Moreover, grazing history provided by NPP help to constrain the origin and dynamics of erosional processes identified from sedimentological or geochemical proxies. In this sense, multi proxy studies including historical documents are crucial to independently test the suitability of the tools used and accurately frame the spatial scale of the different events occurred in a particular area.

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Table 1. Lake Montcortès cores and proxies analysed so far. All data used in this paper belong to the core MON04-1A-1K.

Core	Sampling date	Sediment length	Proxies analyzed	References
MON12-3A-1G	2004	6.2 m	Sedimentology Geochemistry	Corella et al. (2014,2015, 2016, 2017)
MON04-3A-1K	2004	6.2 m	Sedimentology Varve Counting	Corella et al. (2011) Corella et al. (2012)
MON04-4A-1K	2004	5.3 m	Sedimentology Geochemistry Diatoms Varve counting Pollen	Corella et al. (2011, 2016) Scussolini et al. (2011) Rull et al. (2011) ; Rull and Vegas-Vilarrúbia (2014, 2015)
MON07-1A-1G	2007	0.31 m	Sedimentology Geochemistry	Corella et al. (2011)
Physico-chemical parameters Modern analog traps	2012-2015	NA	Varve formation Limnological cycle Modern pollen sedimentation	Trapote et al. (2018) Rull et al. (2017)

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Table 2. Non-pollen palynomorphs (NPP) included in Figures 3 and 4. The table shows identified and unidentified forms with references to the original publications, and includes the code (NPP type) for those morphotypes that were previously assigned to described types following conventions of the NPP community. HdV: Hugo de Vries-Laboratory (University of Amsterdam); UG: University of Ghent; IBB: Botanic Institute of Barcelona; TM: University of Toulouse-le Mirail.

ID	NPP Type	Nature	References
Arnium	HdV-261	Fungal spore	van Geel et al. (2003)
Arthrinium muelleri-type		Fungal spore	Ellis (1971)
Bispora-type		Fungal spore	Ellis (1971)
Cercophora-type	HdV-112	Fungal spore	van Geel (1978)
Chaetomium	HdV-7A	Fungal spore	van Geel (1978)
Coniochaeta cf. l*igniaria*	HdV-172	Fungal spore	van Geel et al. (1983)
Delitschia Type I	IBB-22, UG-1066	Fungal spore	Montoya et al. (2010), Gelorini et al. (2011)
Delitschia Type II (*D. nephrospora*-t)		Fungal spore	Cugny et al. (2010), Macphail and Stevenson (2004)
Diporotheca	HdV-143	Fungal spore	van Geel et al. (1986)
Entorrhiza	HdV-527	Fungal spore	van Geel et al. (1983)
Herpotrichiella-type	HdV-22	Fungal spore	van Geel (1976)
Gelasinospora	HdV-1	Fungal spore	van Geel (1978)
Glomus	HdV-207	Fungal spore	van Geel et al. (1989)
Kretzschmaria deusta	HdV-44	Fungal spore	van Geel (1978)
Neurospora crassa	HdV-55C	Fungal spore	van Geel (1978)
Podospora-type	HdV-368	Fungal spore	van Geel et al. (1981)
Sordaria-type	HdV-55A	Fungal spore	van Geel et al. (1981)
Sordariales		Fungal spore	Bell (2005)
Sporormiella	HdV-113	Fungal spore	van Geel et al. (2003)

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Valsaria	HdV-140	Fungal spore	van Geel et al. (1983)
IBB-3	IBB-3	Fungal spore	Montoya et al. (2010)
IBB-29	IBB-29	Fungal spore	Montoya et al. (2010)
IBB-31	IBB-31	Fungal spore	Montoya et al. (2010)
HdV-495	HdV-495	Fungal spore	van Smeerdijk (1989)
IBB-6	IBB-6	Fungal spore	Montoya et al. (2010)
IBB-23	IBB-23	Fungal spore	Montoya et al. (2010)
TM-O	TM-O	Fungal spore	Cugny et al. (2010)
IBB-9	IBB-9	Fungal spore	Montoya et al. (2010)
UG-1118	UG-1118	Fungal spore	Gelorini et al. (2011)
IBB-18	IBB-18	Fungal spore	Montoya et al. (2010)
Botryococcus	HdV-766	Algal remain	Bakker and van Smeerdijk (1982), Jankovská and Komárek (2000)
Concentricystis		Algal remain	Christopher (1976)
Cosmarium	HdV-332	Algal remain	van Geel et al. (1989)
Debarya	HdV-214	Algal remain	van Geel et al. (1989)
Pediastrum	HdV-760	Algal remain	Bakker and van Smeerdijk (1982), Jankovská and Komárek (2000), Komárek and Jankovská (2001)
Spirogyra	HdV-130	Algal remain	Pals et al. (1980), van der Wiel (1983), van Geel et al. (1983)
Tetraedron	HdV-371	Algal remain	Bakker and van Smeerdijk (1982)
Zygnema	HdV-213, HdV-314	Algal remain	van Geel et al. (1981, 1989)
Acari	HdV-36	Zoological remain	van Geel (1976)
Centropyxis-type		Zoological remain	Charman et al. (2000)
Chironomidae	HdV-219, HdV-907	Zoological remain	van Geel et al. (1989)
Cladocera	HdV-72	Zoological remain	van Geel (1976), van Geel et al. (1983)
Plumatella	HdV-390, HdV-737	Zoological remain	Bakker and van Smeerdijk (1982), van Geel et al. (1981)
HdV-221	HdV-221	Zoological remain	Van Geel et al. (1989)

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Figure 1. Study area. A. General map of the Iberian Peninsula (source: NASA/Caltech). Pyrenees are highlighted by a yellow rectangle. B. Google Earth image of Pyrenees. Montcortès is marked by a star. Other locations mentioned in the text are shown by numbers: 1) Lake Estanya. 2) Pradell fen, 3) Madriu valley, 4) Lake Arreo, and 5) Sourzay peat bog. C. Aerial view of the lake and surroundings (source: gencat.cat).

Figure 2. Summary framework of the main climatic and historical events occurred in the region of LM during the last millennium (HHR and LHR are high and low heavy rainfall events respectively). Main human activities based on pollen data include forest clearance (C), burning (B) and agricultural (A) phases, whereas R refers to recovery of the forest or low anthropogenic activities' periods. Figures and information extracted and modified from Rull and Vegas-Vilarrúbia (2015) and literature therein. The chronology included here follows the original publications.

Figure 3. Percentage diagram of fungal spores. Percentages are based on the pollen sum (see Methods). Significant zones are based on the pollen record (Rull et al. 2011). Coprophilous fungi sum is expressed as both percentage and concentration values. Asterisk marks the non-scaled value of the upper sample, which has been reduced (/10) for more clarity. Calibrated ages (CE) shown are extracted from varve counting analysis (Corella et al., 2012, 2014).

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Figure 4. Percentage diagram of charcoal particles and non-fungal NPP. Percentages are based on the pollen sum (see Methods). Significant zones are based on the pollen record (Rull et al. 2011). Charcoal concentration and pollen sum are plotted for comparison and were extracted from Rull et al. (2011). *Tetraedron* and *Botryococcus* curves are shown in a reduced scale for more clarity. A: Semi-aquatic plant taxa; Z: Zoological remains. Calibrated ages (CE) shown are extracted from varve counting analysis (Corella et al., 2012, 2014).

Figure 5. Lake Montcortès landscape dynamics during the last millennium including vegetation trends extracted from Rull et al. (2011) and land management based on Rull and Vegas-Vilarrúbia (2015) and this work. Agricultural phases (A1 and A2) show the main cultivars based on Rull and Vegas-Vilarrúbia (2015); Ti values are based on Corella et al. (2011); Forest clearings (C1 and C2) and burnings (BI and BII) events are based on Rull and Vegas-Vilarrúbia (2015); Charcoal influx is shown in logarithmic scale, and purple bars show the intervals with occurrence of *Neurospora crassa*; Grazing periods correspond to LM (blue shades, this study) and to regional peaks of coprophilous fungi of other lake records: Lake Arreo (LA; Corella et al. 2013), Sourzay peatbog (SP; Mazier et al. 2009), Pradell fen (PF; Ejarque et al. 2009), and Lake Estanya (LE; Riera et al. 2006).

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APPENDIX A

Description of the new morphotypes recorded in this study. Illustrations of non-identified NPP (IBB types) and Plumatella statoblasts are attached.

IBB-40: Ascospores fusiform, slightly concave (crescent-shaped), 17 x 3.8-5.2 µm, with apical pores. Present as isolated spores or in tetrads (uncommon).

IBB-44: Ascospores one-septate, 10.2-12.6 x 17.4-23.7 µm, slightly constricted at the septum and with paler wall around the apices. It has been tentatively related in this study to *Cordana* (*C. pauciseptata* type) spores (Ellis 1971). *C. pauciseptata* is found on bark and wood of deciduous trees and conifer forests in Europe and North America (Ellis 1971).

IBB-45: Ascospores one-septate, 16-40.3 x 32.7-86 µm, strongly constricted at the septum and marked reticulum. Apical cell ends were found sometimes protruding.

IBB-46: Unknown microfossil fragments including abundant spine protuberances, although they have been always observed broken or uncompleted. Partial remains observed are 12.9 x 17.1 µm in diameter.

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IBB-47: Ascospores fusiform 7.3-11.3 x 13.8-20 µm, with apical pores. Morphology highly similar to the previously described NPP coded as UAB-3 (Revelles and van Geel 2016), which occurred in a soil erosion phase.

Plumatella sp. statoblasts: Asexual structure produced by some bryozoans, 346.3-367.6 x 237.6-276.3 µm, with polygonal cells between 6.8-15.7 µm in diameter. In the NPP literature has previously been named HdV-390A (van Geel et al. 1981)

References

Ellis, M.B. 1971. Dematiaceous Hyphomycetes. The eastern Press Ltd., London.

Revelles, J., Burjachs, F.van Geel, B. 2016. Pollen and non-pollen palynomorphs from the early Neolithic settlement of La Draga (Girona, Spain). Review of Palaoebotany and Palynology, 225: 1-20.

van Geel, B., Bohncke, S.J.P., Dee, H. 1981. A palaeoecological study of an upper Late Glacial and Holocene sequence from "De Borchert", The Netherlands. Review of Palaoebotany and Palynology, 31: 367-448.

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Highlights

- Non-pollen palynomoprhs (NPP) were analyzed in the Pyrenean Lake Montcortès
- NPP provided specific information about human practices for the last millennium
- Coprophilous fungi bracketed four important historical periods of grazing
- Fungal spores related to fire constrained the origin source of fires spatially
- *Glomus* mimicked the Ti values proving its indicative value for erosional processes

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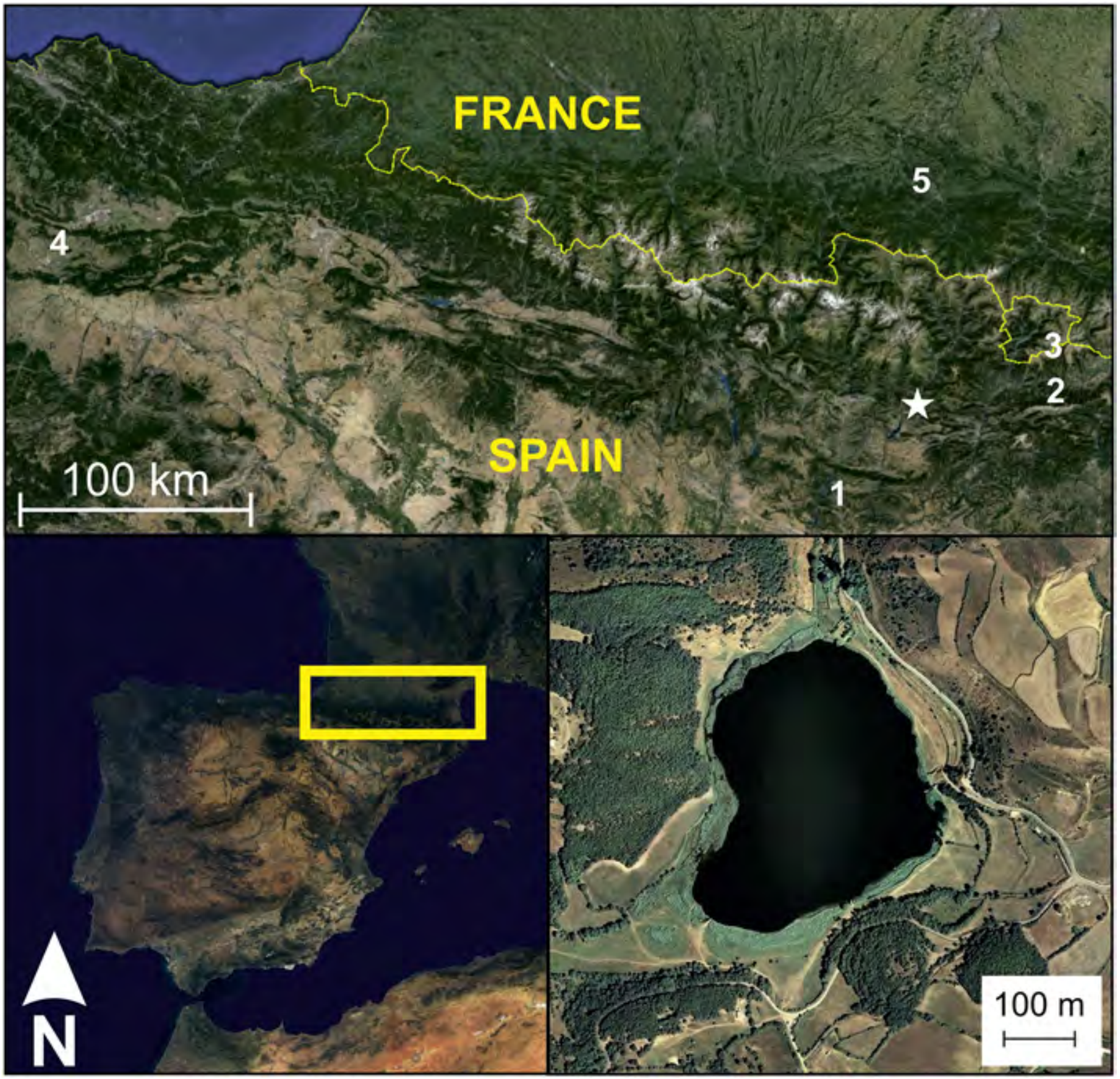

Figure 1

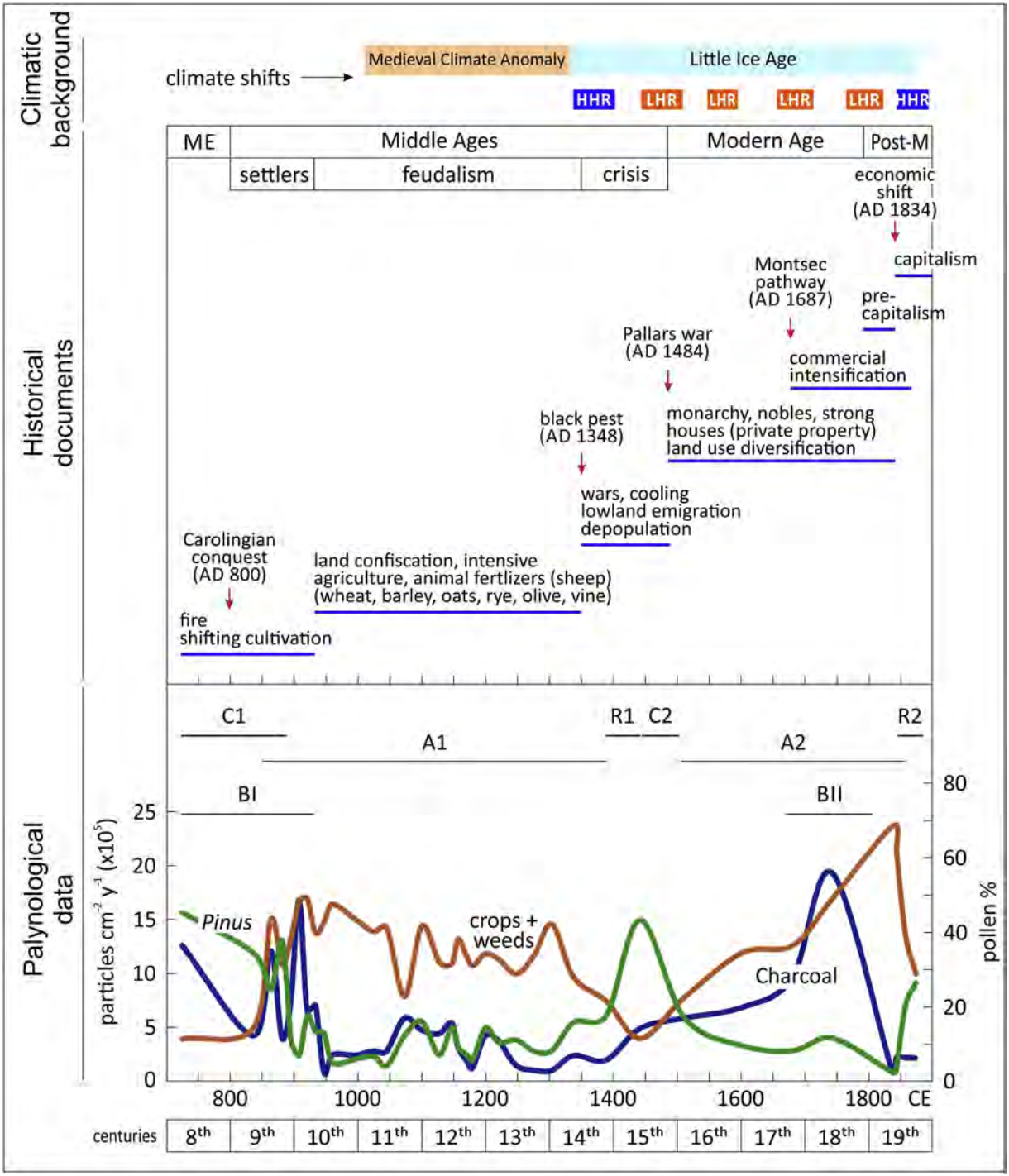
Climatic background
Historical documents
Palynological data
climate shifts
Medieval Climate Anomaly
Little Ice Age
HHR
LHR
LHR
LHR
LHR
HHR
ME
Middle Ages
Modern Age
Post-M
settlers
feudalism
crisis
economic shift (AD 1834)
capitalism
Montsec pathway (AD 1687)
pre-capitalism
Pallars war (AD 1484)
commercial intensification
black pest (AD 1348)
monarchy, nobles, strong houses (private property) land use diversification
wars, cooling lowland emigration depopulation
Carolingian conquest (AD 800)
land confiscation, intensive agriculture, animal fertlizers (sheep) (wheat, barley, oats, rye, olive, vine)
fire shifting cultivation
C1
R1
C2
R2
A1
A2
BI
BII
particles cm-2 y-1 (x10^5)
pollen %
Pinus
crops + weeds
Charcoal
800
1000
1200
1400
1600
1800
CE
centuries
8th
9th
10th
11th
12th
13th
14th
15th
16th
17th
18th
19th

Figure 2

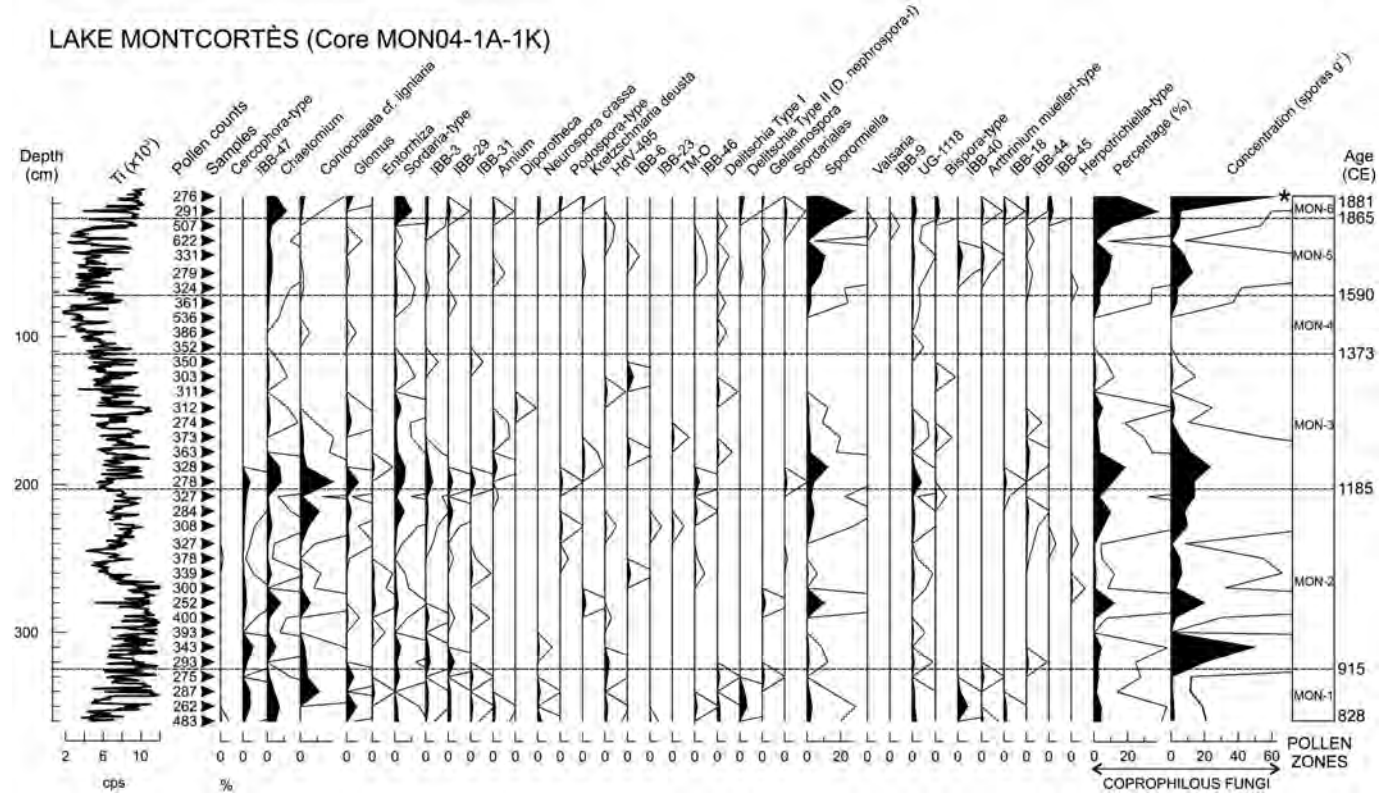
LAKE MONTCORTÈS (Core MON04-1A-1K)
Depth (cm)
Ti (x10³)
Pollen counts
Samples
Cercophora-type
IBB-47
Chaetomium
Coniochaeta cf. lignitaria
Glomus
Entorrhiza
Sordaria-type
IBB-3
IBB-29
IBB-31
Arnium
Diporotheca
Neurospora crassa
Podospora-type
Kretzschmaria deusta
Hdf7-495
IBB-6
IBB-23
TM-O
IBB-46
Delitschia Type I
Delitschia Type II (D. nephrospora-I)
Gelasinospora
Sordariales
Sporormiella
Valsaria
IBB-9
UG-1118
Bisporа-type
IBB-40
Arthrinium muelleri-type
IBB-18
IBB-44
IBB-45
Herpotrichiella-type
Percentage (%)
Concentration (spores g⁻¹)
Age (CE)
MON-6
MON-5
MON-4
MON-3
MON-2
MON-1
1881
1865
1590
1373
1185
915
828
100
200
300
2 6 10
cps
%
0 20 0 20 40 60
POLLEN ZONES
COPROPHILOUS FUNGI

Figure 3

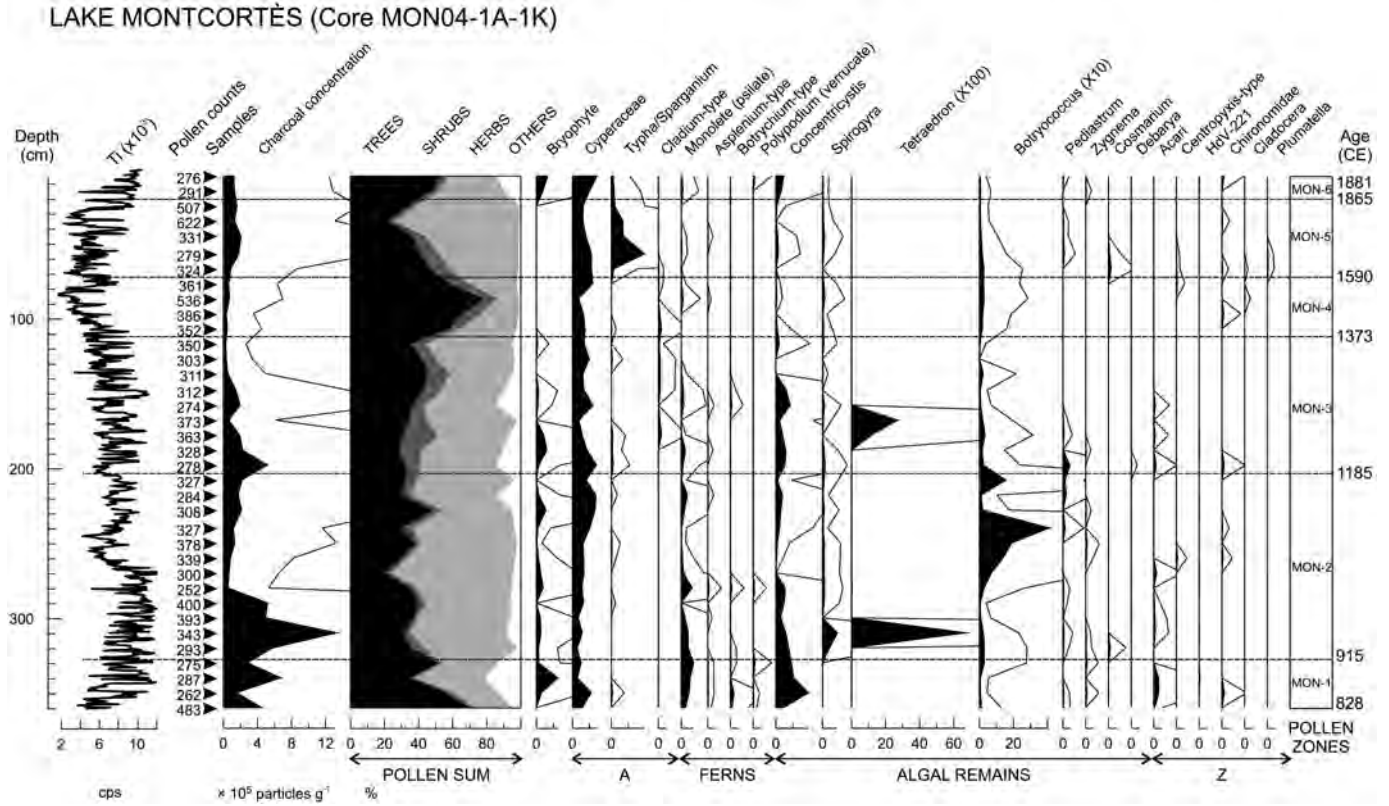
LAKE MONTCORTÈS (Core MON04-1A-1K)
Depth (cm)
Ti (x10³)
Pollen counts
Samples
Charcoal concentration
TREES
SHRUBS
HERBS
OTHERS
Bryophyte
Cyperaceae
Typhe/Sparganium
Cladium-type
Monolete (psilate)
Asplenium-type
Botrychium-type
Polypodium (verrucate)
Concentricystis
Spirogyra
Tetraedron (X100)
Botryococcus (X10)
Pediastrum
Zygnema
Cosmarium
Debarya
Acari
Centropyxis-type
HdV-221
Chironomidae
Cladocera
Plumatella
Age (CE)
MON-6
MON-5
MON-4
MON-3
MON-2
MON-1
1881
1865
1590
1373
1185
915
828
POLLEN ZONES
cps
× 10⁵ particles g⁻¹
%
POLLEN SUM
A
FERNS
ALGAL REMAINS
Z

Figure 4

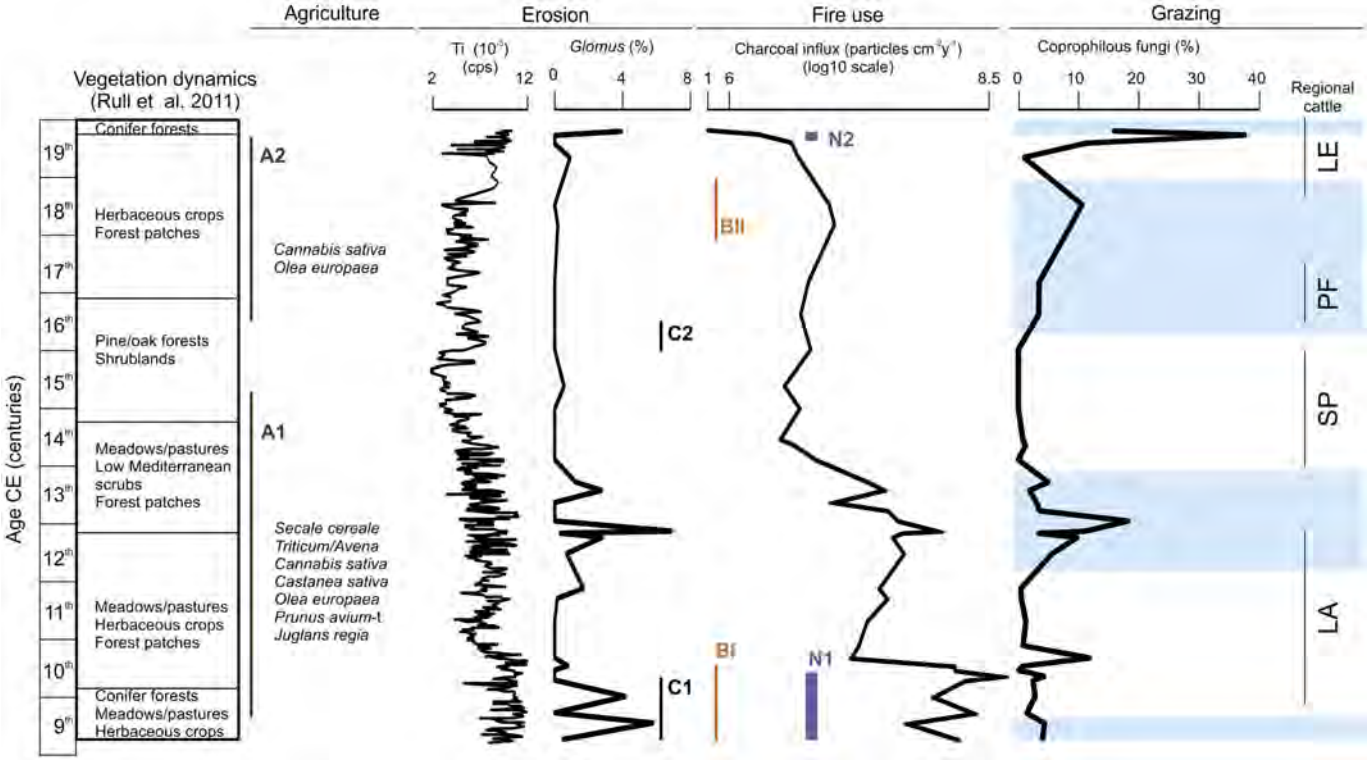
Agriculture
Erosion
Fire use
Grazing
Vegetation dynamics
(Rull et al, 2011)
Ti (10⁻³) (cps)
Glomus (%)
Charcoal influx (particles cm⁻²y⁻¹) (log10 scale)
Coprophilous fungi (%)
Regional cattle
Age CE (centuries)
Conifer forests
Herbaceous crops
Forest patches
Pine/oak forests
Shrublands
Meadows/pastures
Low Mediterranean scrubs
Forest patches
Meadows/pastures
Herbaceous crops
Forest patches
Conifer forests
Meadows/pastures
Herbaceous crops
A2
A1
Cannabis sativa
Olea europaea
Secale cereale
Triticum/Avena
Cannabis sativa
Castanea sativa
Olea europaea
Prunus avium-t.
Juglans regia
C2
C1
N2
BII
BI
N1
LE
PF
SP
LA

Figure 5